Optimal Parameters of High Energy Ion Microprobe Systems Comprised of Oxford Lenses

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Abstract: Focusing of ion beams of MeV energy until now has been mostly accomplished by magnetic quadrupole lenses in different configurations: doublet, triplet, quadruplet and quintuplet. Many focusing systems are two-parametric focusing systems, i.e., systems having two field parameters (two excitations). The simplest two parametric focusing system, other than the doublet, is a two parametric triplet which can consist of two different configurations: (1) an Oxford configuration in which the focusing (F) and defocusing (D) capabilities of the lenses in one plane alternate F-D-F whereas the lens strengths are ordered as A-A-B, and (2) a triplet in which the focusing and defocusing capabilities of the lenses in one plane also alternate F-D-F but the lens strengths are ordered as A-B-A. Experimental results of a comparison of system parameters for these two focusing configurations, including demagnifications, magnet current, and slit settings will be shown. Both configurations utilized the Oxford Microbeams, Ltd. 10 cm long magnetic quadrupole lenses.

Keywords: Ion microprobe; Quadrupole lens; Triplet.
PACS: 41.75.-i; 41-85.-p; 41-85.Gy; 41-85.Lc; 41.90.+e

INTRODUCTION

Focusing of ion beams of MeV energy using a magnetic quadrupole triplet focusing system until now has been mostly accomplished using an Oxford configuration in which the focusing (F) and defocusing (D) capabilities of the lenses in one plane alternate F-D-F whereas the lens strengths are ordered as A-A-B. Alternative magnet configurations which consume less energy, radiate less heat into the laboratory environment, and increase magnet lifespan would be advantageous. The present work introduces a Lafayette configuration based on recent theoretical calculations in which the focusing and defocusing capabilities of the lenses in one plane also alternate F-D-F but the lens strengths are ordered A-B-A. Experimental results of a comparison of the system parameters for these two focusing configurations, including demagnifications, magnet current, and slit settings will be shown. Both configurations utilized the Oxford Microbeams, Ltd. 10 cm long magnetic quadrupole lenses.

ION OPTICS THEORY

In many cases focusing systems have two field parameters (two excitations), i.e., these systems are two-parametric focusing systems. There are two unique two-parametric configurations of the quadrupole triplet lens system. The first one is the Oxford configuration in which the triplet focusing and defocusing capabilities of the lenses in one plane alternate F-D-F whereas the lens strengths are ordered as A-A-B as shown in Figure 1. The second two-parametric triplet, shown in Figure 2, has the Lafayette configuration in which the focusing and defocusing capabilities of the lenses in one plane also alternate F-D-F whereas the lens strengths are ordered as A-B-A. Both configurations are considered with equal lens lengths given by ($l_1 = l_2 =$

CP1099, *Application of Accelerators in Research and Industry: 20th International Conference*
edited by F. D. McDaniel and B. L. Doyle

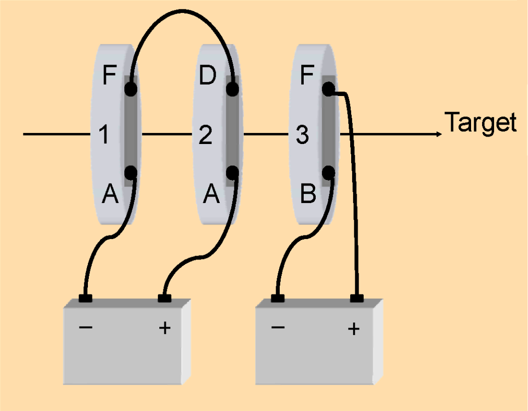

Figure 1. Oxford triplet lens configuration.

$l_3 \equiv l$) and drift spaces s_1 and s_2. Usually, either the first or second mode of excitations are utilized where, in the first mode the demagnifications in two planes are negative, and in the second mode the demagnification in one plane is negative and the demagnification in the other plane is positive. However, the first mode has the smallest magnetic gradients (or the smallest currents through the lenses) and it also gives the smallest aberrations.

In contrast to the Oxford configuration in which only the second mode is available, with the Lafayette configuration it is possible to utilize both modes and this unique advantage of the Lafayette configuration makes it possible to reduce the current requirement while simultaneously minimizing the spherical and chromatic aberrations. For the Oxford magnetic quadrupole lenses (length = 10 cm, aperture diameter = 15 mm) Table 1 provides the theoretical values of several pertinent quantities when the system is presumed to be optimized, including the magnetic field for each of the lenses, B_1, B_2, B_3 at the cylindrical axis of the lens, the demagnifications in each plane, D_x and D_y, the chromatic aberration coefficients, C_{px} and C_{py}, and the spherical aberration coefficients, C_{sx} and C_{sy}. For both triplet configurations and for several emittances optimized slits giving the minimum spot size were numerically determined.

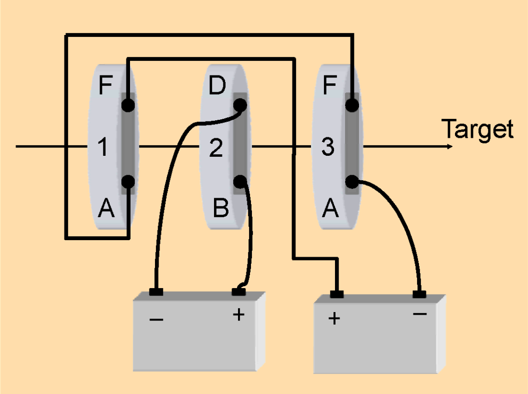

Figure 2. Lafayette triplet lens configuration.

In the Oxford triplet configuration, two adjacent lenses are connected with each other, i.e., +A –A +B and in the Lafayette triplet configuration two outermost lenses are connected with each other, i.e, +A –B +A. A configuration like A +B –B is the doublet configuration where one lens is split into two lenses of the same polarity. In this paper, only the standard Oxford configuration, +A –A +B was compared with the Lafayette triplet configuration +A –B +A.

TABLE 1. Comparison of triplet configuration theoretical quantities.

Quantity	Lafayette Configuration Calculated value	Oxford Configuration Calculated Value
B1	0.719 kgs	1.910 kgs
B2	1.247 kgs	1.910 kgs
B3	0.719 kgs	2.076 kgs
D_x	-18.0522	64.7987
D_y	-9.5322	-19.8219
C_{sx}	9.50177 m	0.670342 m
C_{sy}	6.30921 m	131.514 m
C_{px}	4.12 m	-14.9 m
C_{py}	8.55 m	36.8 m
B_{High}/B_{Low}	1.734	1.087

EXPERIMENT

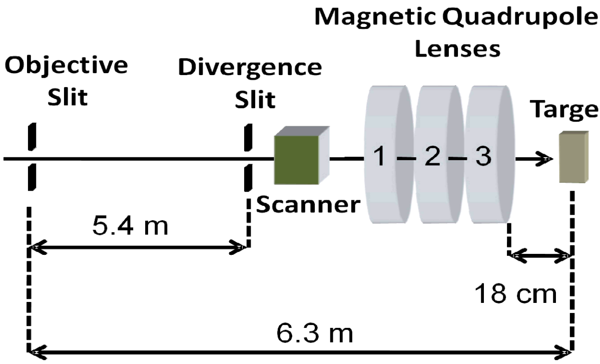

Figure 3. Schematic representation of the high energy focused ion beam microprobe system at the Louisiana Accelerator Center. (image not to scale)

A schematic representation of the high energy focused ion beam (HEFIB) microprobe at the Louisiana Accelerator Center is shown in Figure 3. The system consists of objective and divergence slits, magnetic scanner and magnetic quadrupole focusing lenses in a triplet arrangement. Once the alignment of the system was completed the lenses were electrically connected in the Oxford configuration as shown in Figure 1.

The objective and divergence slits were set to the values indicated in Table 1 and a 3 MeV proton ion beam was manually focused to a spot size of 1.5 μm x 1.5 μm. The beam spot was then scanned across a 2000 mesh scanning electron microscope Cu calibration grid having a hole size of 7.5 μm x 7.5 μm and a 5 μm bar width. As the beam was scanning across the grid, the Cu K_α x-ray emission was used to obtain a PIXE map while scanning transmission ion microscopy (STIM) was also used to provide a STIM map of the grid. The PIXE and STIM maps of the Cu grid using the Oxford lens configuration are shown in Figure 4. The objective and divergence slits were changed to the values indicated in Table 1 and the lenses were then connected electrically in the Lafayette configuration as shown in Figure 2 and the beam was focused to a size of 1.5 μm x 1.5 μm and then scanned across the Cu grid to obtain both PIXE and STIM maps shown in Figure 5. The current on target was approximately 50 pA for the Lafayette configuration and 100 pA for the Oxford configuration.

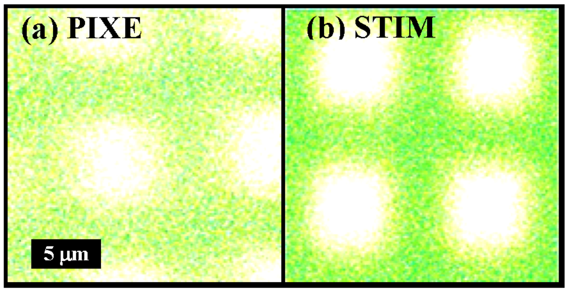

Figure 4. (a) PIXE , and (b) STIM maps obtained with a 3 MeV proton beam focused with the triplet lenses in the Oxford configuration.

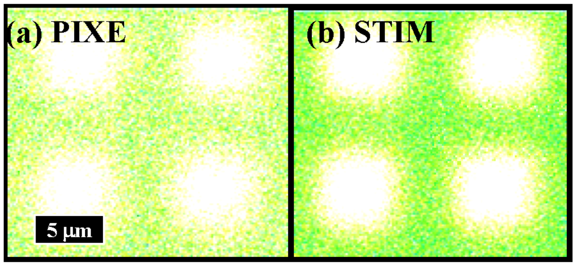

Figure 5. (a) PIXE , and (b) STIM maps obtained with a 3 MeV proton beam focused with the triplet lenses in the Lafayette configuration.

Since it was anticipated that the required current in the magnetic lenses for the Lafayette configuration would be much less than the current required for the Oxford configuration, a test was performed to determine the temperature increase in the magnetic lens yokes as a function of the magnet current. This test consisted of using a Platinum: Platinum-10% Rhodium thermocouple wire attached to one of the magnet yokes to determine the equilibrium temperature for currents up to 60 A, a value which was higher than the maximum value of the magnet current used to focus a 3 MeV proton beam with the Oxford configuration. To obtain the equilibrium temperature of the yoke for each current, the yoke was allowed 30 minutes to reach an equilibrium temperature after the current had been increased by 5 A before the temperature was measured. Figure 6 shows the temperature change in the yoke as the current was increased (the estimated error in the temperature measurements is ±1°C). Also indicated in Figure 6 is the yoke temperature at the highest current in each configuration.

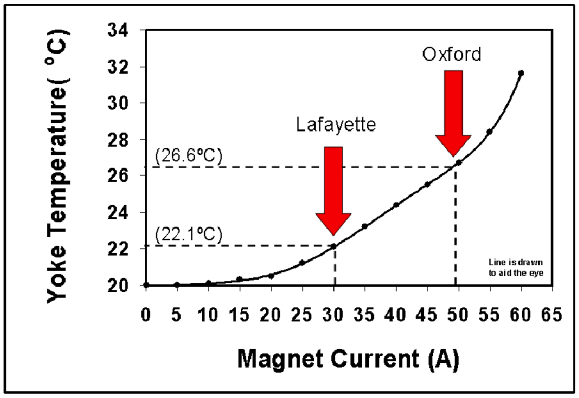

Figure 6. Results of temperature measurement on outer yoke of quadrupole magnet performed with Platinum:Platinum-10% Rhodium thermocouple wire. (Error approx. ±1°C)

RESULTS

As seen in Table 1, for both configurations, the ratio of the highest to lowest values of the theoretical values of the magnetic fields compares very well with the ratios of the corresponding magnet currents

TABLE 2. Comparison of triplet configuration experimental quantities.

Experimental Quantity	Lafayette Configuration Experimental Value	Oxford Configuration Experimental Value
Emittance	$3.53 \times 10^{-19}\,m^2$	$6.53 \times 10^{-19}\,m^2$
Beam Current	~ 50 pA	~ 100 pA
Obj Slit	40 μm x 22 μm	64 μm x 20 μm
Div Slit	286 μm x 654 μm	650 μm x 366 μm
Q_1	17.43 A	47.47 A
Q_2	30.48 A	47.47 A
Q_3	17.45 A	49.73 A
Q_{High}/Q_{Low}	1.747	1.048

required for focusing the beam shown in Table 2. As seen in Table 1, the theoretical values of the spherical and chromatic aberration coefficients are significantly lower for the Lafayette configuration. It is also seen from Table 2 that the Lafayette configuration requires much less maximum current for focusing than the Oxford configuration which results in a much lower equilibrium temperature of the magnet yoke. It should be noted that in the Oxford configuration, two lenses will require the higher current while in the Lafayette configuration, the converse is true, i.e., two lenses require the lower current. This means that the actual resistive heating of the Lafayette configuration will be much lower than the same system using Oxford configuration.

CONCLUSIONS

The two parametric magnetic quadrupole triplet focusing system operating in the Lafayette configuration has been shown to be a viable alternative to the Oxford configuration. The Lafayette configuration produces a comparable beam spot size while focusing with substantially less magnet current, thereby reducing radiant heating effects and increasing magnet lifespan.

For an ion with mass M, energy E (MeV), and charge state q, the focusing power of a microprobe system is proportional to the ratio ME/q^2 which, in turn, is proportional to the excitation current. For a 3 MeV proton beam focusing by the Oxford configuration, this ratio is 3. The current required in the Oxford configuration is very near the maximum allowable current in the magnets (due to heating and field saturation) and therefore precludes any significant increase in this ratio. However, because the Lafayette configuration requires less than 50% of the current needed in the Oxford configuration, the current can be increased by approximately a factor of 2 without any undue thermal stress or field saturation effects. Therefore, the use of the Lafayette configuration can enable the ratio ME/q^2 to be as high as 6, thereby allowing focusing of other heavier ions, such as 3 MeV He^{2+}.

ACKNOWLEDGEMENTS

The Louisiana Governor's Biotechnology and Information Technology Initiatives

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